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Models of the effects of weather on the yields of Silage Maize

Principles

The general principle which has been followed is that the crop is capable of producing a 'potential' yield under ideal conditions. This yield cannot be exceeded, but weather factors can exert an influence so as to reduce the yield below the potential. The aim of the models is to modify the potential yield by weather factors so as to obtain actual yields. Silage maize yield data (for the variety INRA 200) was available for 11 years from Wytham near Oxford. Two approaches have been used.

1) The potential yield can be specified and weather factors then applied to give an actual yield. The potential yield is then varied so as to give the best fit to the yield data.

2) A more fundamental approach is to calculate the carbohydrate production from weather data and crop characteristics and then to allow for respiration losses, so as to arrive at a final yield figure.

Model 1

The model is based upon that due to Russo and Knapp (1976) (Russo J M & Knapp W W "A Numerical Simulation of Plant Growth" Int. J. Biometeor. 1976, Vol 20, No. 3, pp 276-285). An idealised growth curve is used which gives the increase of potential yield with time. Russo et al used a 'S-shaped' curve, but in this model it is simplified to three straight lines. The gradient of the central portion is three times that of the other two. (See figure 1).

The time axis is then divided into intervals, and for each interval weather conditions are obtained. Provided the effects of each weather variable on yield can be expressed as a departure from the optimum then the actual yield increment during a time interval is

$$A = P \times TCx \quad PC \times WC \qquad (1)$$

A = actual yield increment
P = potential yield increment
TC = coefficient giving the fractional reduction below optimum yield due to temperature
PC = coefficient giving " " " " " " " to radiation
WC = coefficient giving " " " " " " " to water

A is calculated for each time interval, and then the A's are added to obtain the total yield.

The units of the time axis are not in days, but in biometeorological time since the rate of plant development also depends upon the weather. Ontario Units are a good way of expressing maize development and it is possible to redraw fig 1 from curves given by Phipps et al (1975) (Phipps R H., Rosemary J Fulford, Crofts F C "Relationships between the production of forage maize and accumulated temperature, Ontario Heat units and solar radiation" Agricultural Meteorology 14(1975), 385-397) (See figure 2).

FH2B

It so happens that in general the portion of the curve between 500 and 900 o.u. corresponds to June, 2000 o.u. are normally accumulated by the end of August and 2500 by the end of September. This implies that monthly weather data can be used which simplifies the problem considerably.

Temperature Coefficient

Maximum yields are assumed to occur when the mean daily air temperature is between 21.1°C (70°F) and 28.9°C (84°F) with a fall as the temperature rises above or below this. Yields fall to zero when the mean air temperature is 10°C. The variation between 10°C and 21.1°C is given by (See Russo et al. (1976)).

$$TC = \text{Tanh}\left(\pi \cdot \frac{t-10}{21.1-10}\right) \qquad (2)$$

t = daily mean temperature °C

Radiation Coefficient

Maximum yields are assumed to be obtained when the daily mean short wave radiation is 600 cal/sq cm or above. Yields fall linearly to zero when the daily mean radiation is 15 cal/sq cm.

$$PC = 0.001709R - 0.0264 \qquad (3)$$

R = daily mean radiation (cal/sq cm)

Short wave radiation is obtained from sunshine hours using the regression

$$R = 59.RA\ (0.16 + 0.62\ n/N) \qquad \text{(cal/sq cm)} \qquad (4)$$

n = daily mean sun hours

N = daylength

RA= short wave radiation in the absence of clouds and atmosphere.

Water Coefficient

The coefficient WC is taken to be the ratio of actual to potential transpiration. A model of water use by maize is given below (and Ag. Memo. 823).

Let P be the potential transpiration calculated for a short crop such as grass, then the model for maize makes some allowance for the changes in transpiration for tall crops, especailly for intercepted rain.

The Water Use Model is as follows:

April and May

Bare soil is assumed

First	25 mm	of soil	moisture	E = P
Next	8 mm	"	"	E = 0.3P
Next	2 mm	"	"	E = 0.1P

(From Ag. Memo. 580)

June

Assume limited rooting depth and soil cover by seelings.

First	35 mm	of soil	moisture	E = P
Next	35 mm	"	"	E = 0.5P
Next	25 mm	"	"	E = 0.25P

July

Intercepted rain evaporates at E = 1.5P (Maximum interception = 0.5mm)

Then:

First 75 mm of soil moisture E = 1.2P
Next 50 mm " " " E = 0.5 (1.2P)
Next 25 mm " " " E = 0.25 (1.2P)

August and September

Intercepted rain evaporates at E = 2P (Maximum interception 0.5mm)

First 75 mm of soil moisture E = 1.3P
Next 50 mm " " " E = 0.5 (1.3P)
Next 25 mm " " " E = 0.25 (1.3P)

The moisture balance procedure enables the changes in soil moisture to be obtained for each month and hence the actual evaporation.

After TC, PC and WC have been calculated from Monthly Weather data a value of potential yield is chosen. The literature suggests this could lie in the range 20 to 50 t/ha. Monthly potential yield increments are then calculated as one-eigth the potential in June and September and three eights for July and August. This potential monthly yield is multiplied by the monthly coefficients for temperature, radiation and water. In addition the June value is multiplied by 0.33 to allow for incomplete crop cover. Different values of potential yield are tried for all eleven years until the actual yields obtained are closest to the observed yields.

Example

Year 1961 Potential yield = 40 t/ha

	TC	PC	WC	Monthly yield increment t/ha	Total yield t/ha
June	0.91	0.24	0.68	0.74	0.74
July	0.95	0.62	0.75	6.64	7.38
August	0.95	0.53	0.72	5.45	12.83
September	0.93	0.36	0.83	1.39	14.22

The observed yield for that year was 13.5 t/ha

The potential yield which fitted all the data best was 37.8 t/ha and the comparison for the 11 years is given in table 1.

In the paper of Russo et al (1976) the radiation coefficient was represented by the hyperbolic tangent form:

$$PC = \text{Tanh}\left(\pi C \cdot \frac{R-15}{585}\right)$$

The use of this coefficient gave a slightly lower mean error as compared with the linear PC as used above (eq. 3), but required a potential yield of 22.2 t/ha. This large variation of potential yield with the form of the coefficient is clearly not satisfactory. It seems sensible then to calculate the carbohydrate production

each year by using observed radiation and then to modify this potential production by temperature and water coefficients. This is the basis of model 2.

Model 2

Maize photosynthesis is calculated according to the method given by Monteith (1965). ("Light distribution and photosynthesis in field crops". Ann. Bot. Lond., (N.S.), vol 29, p 17-37), and set out in Ag. Memo. 386.)

Photosynthesis P (gm carbohydrate per m^2 leaf area per hour) is given by

$$P = (a + \frac{b}{I})^{-1} \qquad (6)$$

$b = 0.05$ cal/gm

I is in cal/cm^2/min

and the value of 'a' depends upon temperature. Using de Wit et al's (1971) ('Potential Crop Production' Wareing PF and Cooper JP eds. Heinemann Page 120) table to assess the effect of temperature on P

$$a = 0.118/(0.0584.T - 0.344) \qquad (7)$$

T is the temperature of the leaves during photosynthesis. It seems reasonable to make T equal to the mean daylight temperature. From Ag . Memo. 16 this is

$$T = MAX - 0.39\ (MAX-MIN) \qquad (8)$$

for June, July and August

$$T = MAX - 0.35\ (MAX-MIN) \qquad (9)$$

for September

MAX = monthly mean maximum temperature
MIN = monthly mean minimum temperature

In order to find the photosynthesis per unit land area it is necessary to find the area of sunlit leaves A0, and the area of once-shaded leaves A1, for which the mean light intensity is reduced to one tenth of the intensity at the top of the crop. A0 and A1 are expressed in terms of leaf area index L and a number S which is the fraction of incident radiation which passes through unit leaf area without interception. For maize S is taken to be 0.7.

$$A0 = (1-S^L)/(1-S) \qquad (10)$$

$$A1 = (1-S^L - (1-S)LS^{L-1})/(1-S) \qquad (11)$$

The mean leaf area index for June is taken to be 0.5, for July 3.0 and for August and September 4.0. The formulae given by Monteith then allow the calculation of gross photosynthesis as a monthly mean value in t/ha/day. Monthly totals are obtained by multiplying by the number of days in the month. So far we have allowed for radiation and temperature. The effect of water is allowed for as in Model 1 by multiplying the calculated gross photosynthesis by WC, the ratio of actual to potential transpiration.

Thus, for any month we have an estimate of the carbohydrate that was available to the plant. Not all of this ends up as yield, some is lossed through respiration. Biscoe and Gallagher (1977) quote a relation which gives total respiration as the sum of synthesis respiration, which is used by the plant in making new-cells; and maintenance respiration, which maintains the existing structure. Synthesis

respiration is a constant fraction (0.33) of gross photosynthesis calculated above. Maintenance respiration is a fraction of the dry weight of the plant, with this fraction depending upon temperature according to a temperature coefficient (Q_{10}) relation:

$$R_2 = R_1 Q_{10}^{(T_2-T_1)/10} \qquad (12)$$

R1 and R2 are the respiration rates at temperatures T1 and T2 respectively.

The maintenance respiration is then

$$\text{Dry weight} \times 0.014/(2^{(20-TM)/10}) \qquad (13)$$

where 0.014 is the fraction of dry weight used in maintenance respiration for TM = 20°C. Since respiration takes place throughout the 24 hours TM refers to mean daily temperature calculated as the mean of maximum and minimum air temperature. A time step of one month is rather long to estimate maintenance respiration accurately and to get a better estimate the time step was reduced to 1 day, but using monthly mean daily rates for photosynthesis, synthesis and maintenance respiration.

Calculations were started on June 1st when dry weight was taken as zero. The dry weight yield at the end of the first day was obtained as (1-0.33) of the daily mean photosynthesis. The calculations were then done for day 2 with maintenance respiration calculated for the dry weight obtained from day 1. For day 3 the calculations are done using maintenance respiration obtained from day 2's dry weight, and so on to the end of September. The program prints out photosynthesis, respiration losses and current dry weight yield.

A correction was applied to the photosynthesis calculations in order to make some allowance for the linearising effect of using monthly mean radiation in equation (6). The correction was evaluated as follows: daily radiation totals in the range between totally sunless and totally cloudless days were allocated uniformly to the days of the month in ten equal intervals. Thus 3 days in the month were cloudless, 3 days were completely sunless and the remaining 8 radiation classes were each given 3 days each. For 31 day months the average radiation value had 4 days. This frequency distribution for radiation is approximately what happens in nature (Brooks and Carruthers ... Statistical Methods in Meteorology). Calculations of photosynthesis done using the radiation according to this distribution were then compared with photosynthesis obtained from the monthly mean calculation. In general, monthly mean figures overestimate dry matter production by about 4.3%. Finally some allowance was made for roots which are not harvested, and 10% of total dry matter production was assumed to go to roots.

EXAMPLE

1961

	WC	Radiation cal/sq cm/day	Gross Photosynthesis T/ha/month	Respiration t/ha/month Synthesis	Maintenance	Yield/month t/ha	Yield t/ha
June	0.68	432	4.41	0.99	0.27	1.73	1.73
July	0.75	378	18.09	4.48	1.85	7.25	8.98
August	0.72	327	18.68	4.46	3.96	5.10	14.08
September	0.83	224	13.13	3.60	4.86	2.44	16.52

Allowing for the linearising effect of using monthly mean radiation gives 15.81. Less 10% for roots gives 14.22.

Table 1

Comparison between model (2) and model (1) and actual yields (t/ha)

Year	Actual	Model (2) (Monteith)	Model (1)	Potential Yield = 37.8 t/ha
1960	15.7	16.32	14.20	
1961	13.5	14.22	13.49	
1962	12.2	15.20	12.38	
1963	15.4	15.46	13.37	
1964	9.1	9.06	10.63	
1965	14.2	15.71	13.20	
1966	15.5	16.4	14.73	
1967	14.6	15.06	15.21	
1968	13.0	16.4	14.15	
1969	13.7	14.19	14.53	
1970	16.5	12.76	12.41	

Discussion

The yields from Model (1) look better just because the potential yield has been adjusted to give the minimum difference between actual and model yields. Yields from Model (2) are nearly all systematically larger than actual yield although the agreement is reasonable. The year 1970 was not handled well by either model. This was a rather dry season and the yield of 16.5 t/ha, which was the highest in the 11 years, was almost certainly due to irrigation (E S Bunting private communication). 1964 was a very dry season and the coefficient WC seems to have coped quite well. It would appear that yield is mainly determined by water supply and that cool summers which give slow development can give reasonable yields provided that moisture is present and that at least 2500 Ontario Units have been accumulated by harvest.

Further refinements which could be incorporated include:

1) Variable leaf area index. At the moment this is constant for each month, but the build up of leaf area and leaf death each year obviously depends upon weather conditions especially temperature and water supply.

2) Calculations based upon Ontario Units rather than calendar months. This would make a difference in unusually warm/cold seasons.

3) Improved expression for WC. The present model assumes WC=1.0 up to a soil moisture deficit of 75 mm (July to September). This could well prove too optimistic and may have to be revised.

The plot trial yields tend to be slightly lower than yields calculated from plant characteristics and weather. The differences are presumably due to the factors (1) to (3) above together with variations in nutrient availability. Although maize does not suffer unduly from disease it does on occasion suffer badly from Fusarium which may reduce yields.

Actual farm yields are about one half of these plot trial yields. The reasons for this are probably:

1) Reduction of plant populations (and hence leaf area) due to pests, seed diseases, poor seedbeds, inadequate or wrongly applied fertilizers.

2) Weed competition.

3) Soils with lower available water capcity, or with pans or restricted deapth.

4) Harvest losses

In order to assess the importance of plant population the model was run with the leaf area index reduced by 1/3 throughout the life of the crop. The assumption was made that this would not affect the water balance calculations. This leaf area reduction is equivalent to a target plant population of 90,000 per hectare reduced to 60,000 per hectare. Yields of silage were reduced by 23%.

In order to assess item (3) above, the model was run with a lower maximum available water capacity (115 mm) compared with the normal water availability equal to 150 mm. All other water availabilities were reduced in the same proportion. This light soil is by no means the worst that could be encountered but may represent a typical poorer type of soil that maize may be grown in, say in order to achieve higher seedbed temperatures. For the eleven years 1960 to 1970 only 1964 was very dry and the lighter soil caused a yield reduction of 21%. Most yield reductions were about 3% with a range from 0% to 5%.

These yield reductions seem rather small. However, maize passes through the high transpiration months of May and June in a seedling state with a constantly enlarging root system. This means that more and more soil moisture becomes available as the season advances. It requires very dry conditions in mid to late summer (not very common in UK) to produce substantial yield reductions.

Thus it would appear that lack of plant population is an important factor in loss of yield with soil type important in dry seasonswhen yields would be low anyway. It is probable that much of the field to field yield varialibity, which is characteristic of maize, is due to changes in plant population.

Any comments should be sent direct to the author.

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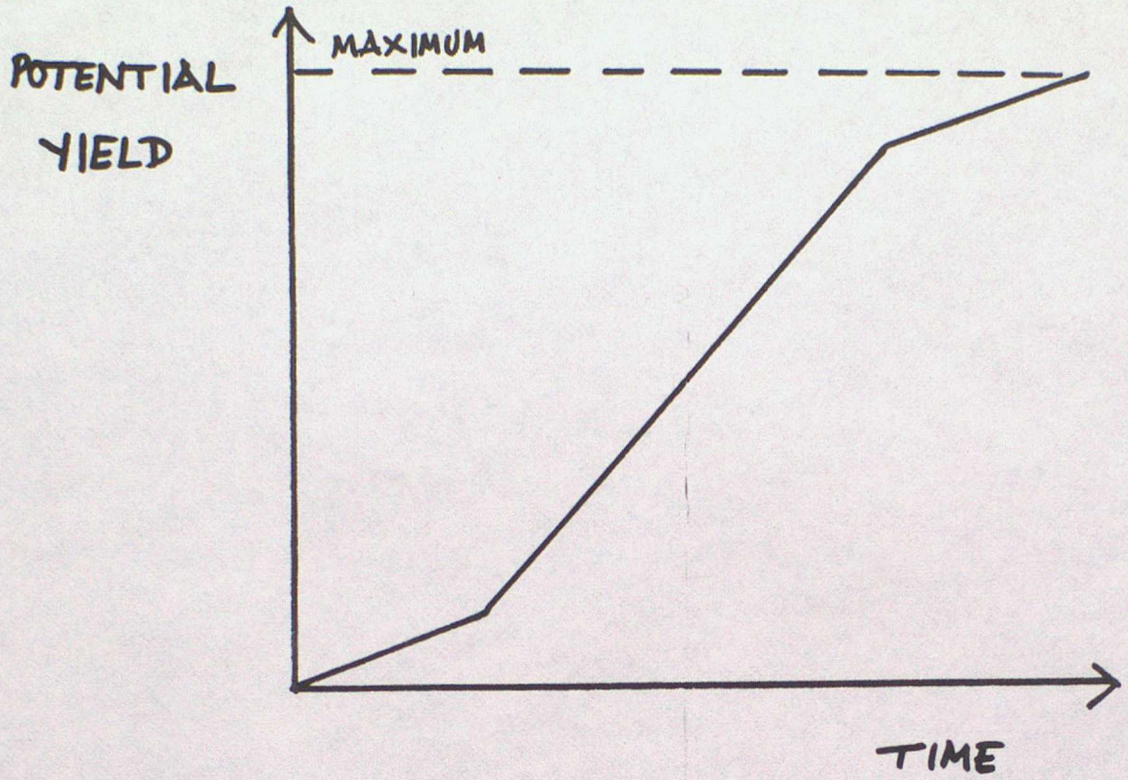

FIG 1. VARIATION OF POTENTIAL YIELD WITH TIME.

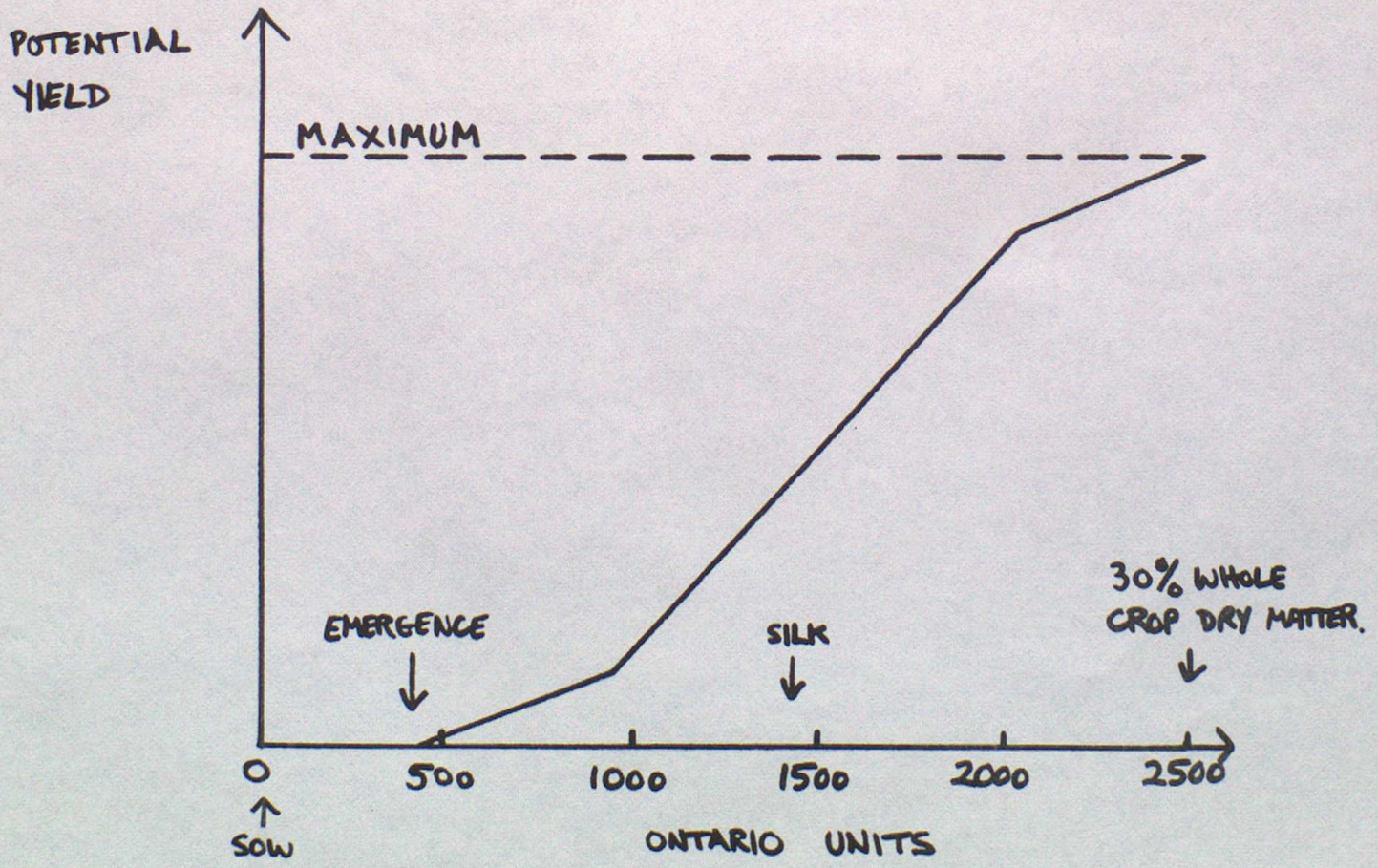

FIG 2. VARIATION OF POTENTIAL YIELD WITH ONTARIO UNITS.